NASA Technical Paper 3601

A Guidance Scheme for Automated Tetrahedral Truss Structure Assembly Based on Machine Vision

William R. Doggett
Langley Research Center • Hampton, Virginia

National Aeronautics and Space Administration
Langley Research Center • Hampton, Virginia 23681-0001

November 1996

Available electronically at the following URL address: http://techreports.larc.nasa.gov/ltrs/ltrs.html

Printed copies available from the following:

NASA Center for AeroSpace Information
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 487-4650

Abstract

The Automated Structures Assembly Laboratory (ASAL) is a unique facility at Langley Research Center used to investigate robotic assembly of truss structures. An industrial robot equipped with a special purpose end-effector has been used to assemble 102 struts into either an 8-m-diameter structure or a beam-like structure. Initially, robot motions required to construct the structure were developed with iterative manual procedures. However, this approach is not suitable for in-space applications because of astronaut time and safety considerations. Thus, an off-line geometric path planner combined with a compact machine vision system has been developed. By providing position information relative to passive targets on the structure, the vision system guides the robot through a critical region, beginning approximately 12 in. from the structure and proceeding to a position where the structure is grasped prior to strut insertion. This approach offsets model uncertainties in the path planner and greatly increases operational reliability. This paper presents details of the machine-vision-based guidance algorithms used during structure assembly.

1. Introduction and Assembly System Description

The Langley Research Center conducted a research program to develop methodologies for automated in-space assembly of large truss structures. Such structures have been proposed for orbiting and lunar antennae, orbiting platforms, and aerobrakes (refs. 1 and 2). In addition, many proposed lunar missions include large structures that would be viable candidates for assembly, such as the large lunar telescope (ref. 3). Within the Automated Structures Assembly Laboratory (ASAL), a regular tetrahedral truss structure has been assembled, using a specialized end-effector mounted on an industrial robot.

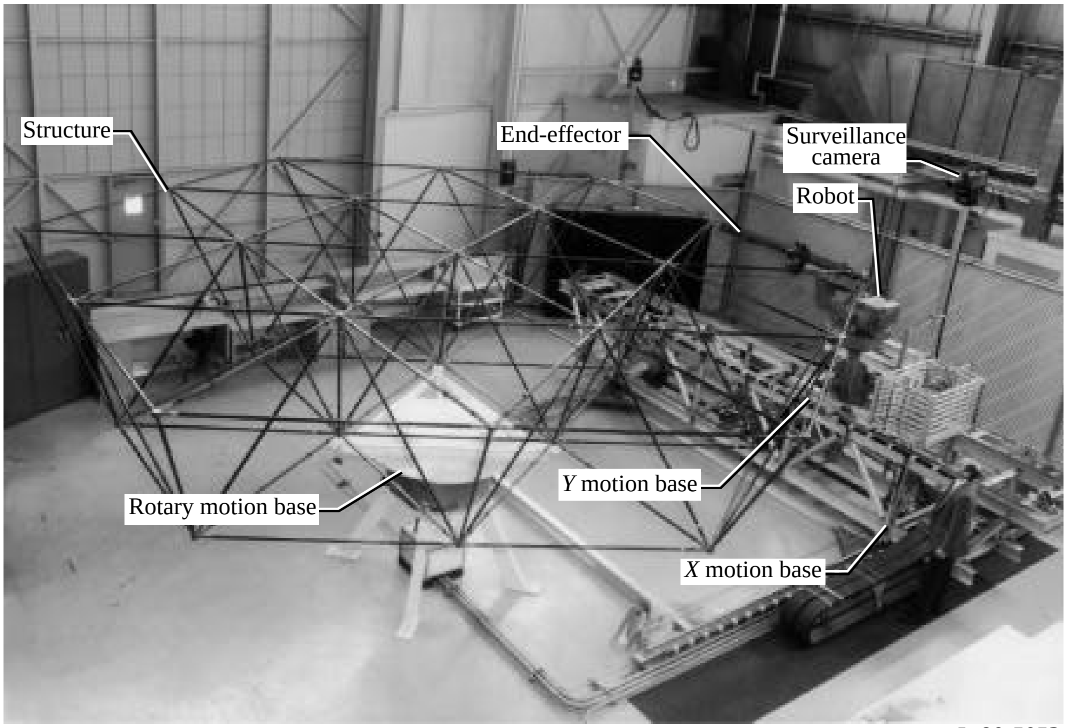
This paper describes the operation of the guidance algorithms used in the ASAL during automated strut installation. The algorithms and strategies provide a significant improvement in system robustness yet are simple to implement. Details of problems encountered during the algorithm development and their solutions are discussed. The paper concludes by identifying areas available for further investigation.

1.1. Facility Description and Background

The ASAL, depicted in figure 1, includes three motion bases, an industrial robot, a special purpose end-effector, and surveillance cameras. The truss structure is assembled on a rotary motion base, visible in the center of the figure, that presents the unfinished portion of the structure to the robot. The robot, on the right of the figure, rides on two linear motion bases that position it for strut installation. The robot is a commercially available six-degree-of-freedom manipulator arm with a 60-in. reach and a 30-lb payload capacity. No custom modifications of the robot were required to support assembly operations. A special purpose end-effector was designed to insert and secure a truss member into the structure. This specially designed end-effector is symmetric about its center. Figure 2 shows the left side of the end-effector. During the assembly process, the end-effector uses receptacle fingers to grasp the structure so that a strut can be inserted and secured to a receptacle (fig. 3). Reference 1 provides further details about the assembly system components and process.

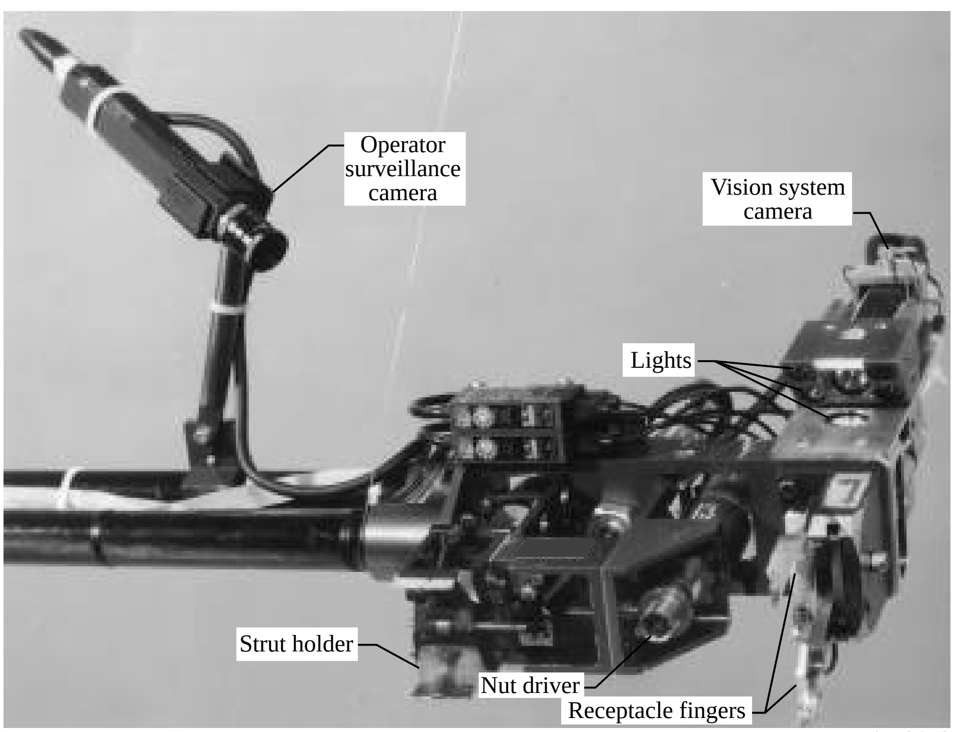
Automated assembly operations initially used taught paths for robot motion during hardware and assembly validation tests. The paths are taught by manually positioning the robot in a desired configuration, which is stored. Then the robot is repositioned, and the new configuration is stored. This process is repeated until the sequence of configurations, or path, is created. The path is then given a name for later execution. When the path is executed, the robot moves through each configuration sequentially, linearly interpolating between the specified configurations.

Taught paths were successful because position errors were consistent in the laboratory environment. Although large variations experienced in the ground test are not expected in space because of the absence of gravity, the strut separation distance is expected to vary randomly because of slight differences in the strut lengths, small misalignments in the truss hardware, slight differences in joint locking torque, and random vibrations. A viable automated system must be capable of identifying and locating certain features on the structure to be used as reference points for guiding the robot and end-effector into position for strut installation. The robot motions



L-90-5053

Figure 1. Automated Structures Assembly Laboratory.



L-92-8653

Figure 2. Close-up of left side of strut end-effector.

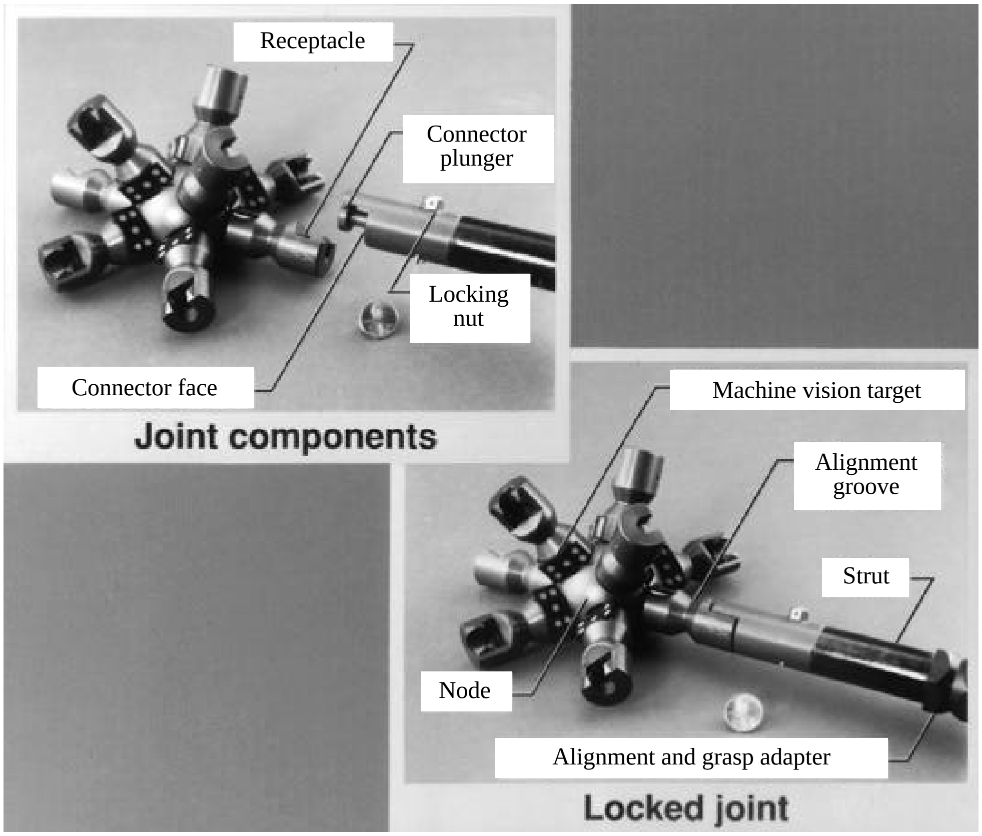


Figure 3. Truss structure hardware.

would be performed in three segments, as shown in figure 4, each with a different mode of control. These segments are

1. Gross motions between the storage tray and the vision approach point (VAP) would follow a collision-free path generated by an automatic path planner, based on geometric models of the robot and structure.
2. From the VAP, machine vision would be used to guide the end-effector to a point where the structure can be grasped by the receptacle fingers.
3. Finally, force-torque feedback would be used for final, precise alignment in preparation for strut insertion.

1.2. Truss Hardware and Passive Vision Targets

The automated assembly system can be configured to construct planar structures or beam structures. In contrast to other designs (ref. 4), the structures are based on a generic locking mechanism that makes it possible to replace individual elements in the structure without impacting the surrounding elements. This paper focuses on construction of the planar geometry, composed of 102 struts, that forms a structure 8 m in diameter.

Figure 3 shows the hardware used to assemble the truss structure. The nodes are used to position the receptacles to form a specific structural geometry. The receptacles include an alignment groove that is grasped by the end-effector's receptacle fingers to fix the end-effector position during strut installation. In addition, the receptacle forms half of the joint used to secure the struts within the structure. The other half of the joint, which is affixed to the strut, includes a locking nut that is actuated by the nut driver on the end-effector (fig. 2) to secure the joint. The alignment and grasp adapter (fig. 3) is shaped to maintain the strut in a precise location and orientation when grasped by the strut holder (fig. 2). A detailed description of the truss hardware appears in reference 1.

The vision system consists of a miniature charge-coupled device (CCD) video camera and five lights contained in a compact housing mounted on the end-effector. The vision system's targets, used to locate the receptacles, are mounted at the base of the receptacles (fig. 3). Details of the vision system and pattern recognition algorithms appear in reference 5.

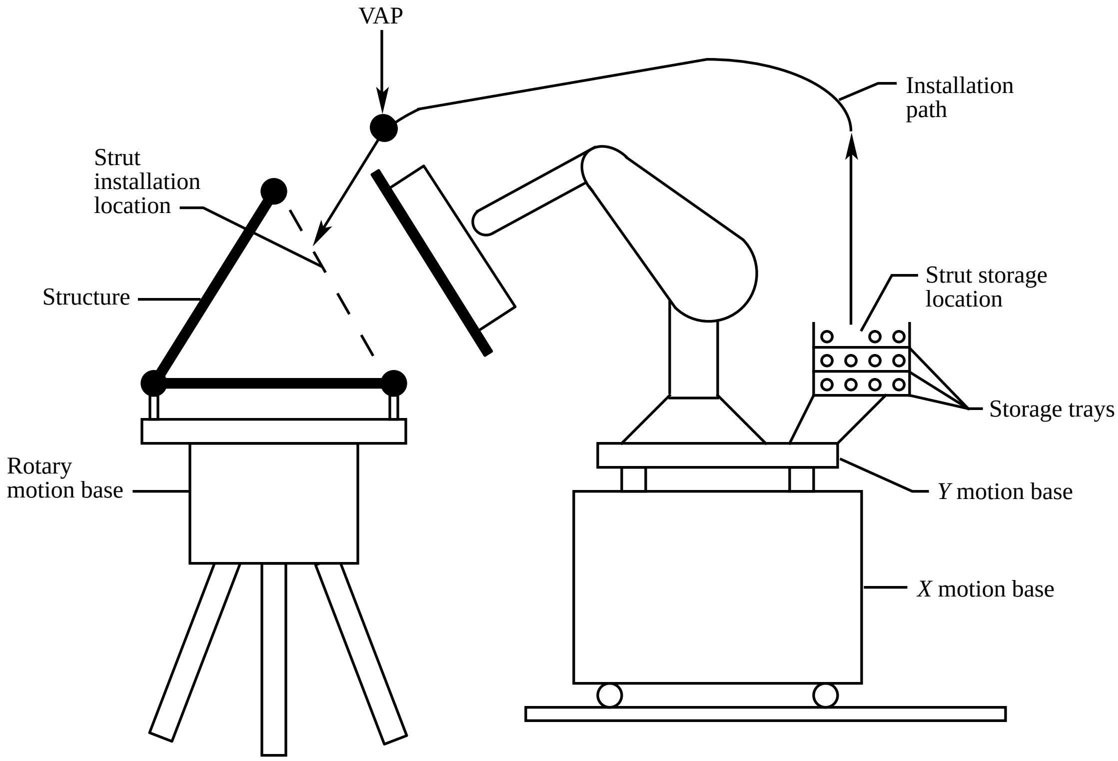


Figure 4. Facility side view depicting strut installation path.

1.3. Automated Assembly Operations

Assembly begins at the center of the structure and moves radially outward. A script specifying the order of strut installation defines the assembly sequence. The script executes on an executive computer, which coordinates the operation of special-purpose computers used during assembly. One computer is dedicated to motion base positioning, another to image processing, and the third to end-effector monitoring and control (ref. 6).

To begin installation of a strut, the robot acquires the strut from its known location in the storage tray positioned behind the robot (fig. 4). The strut is grasped by strut holders that close on the alignment and grasp adapters affixed to the strut. The motion bases are then positioned so that the robot can reach the strut installation location in the structure. The robot moves along a predetermined installation path to the VAP, located approximately 12 in. from the intended installation point in the structure. From the VAP, vision-based guidance algorithms direct the robot to a point where the structure may be grasped for strut insertion.

Vision-based guidance algorithms compensate for inaccuracies in the geometric model of the structural assembly system that prevent strut installation based solely on preplanned paths. In ground tests within the ASAL, model inaccuracies are dominated by the gravity-induced deflections and absolute positioning errors inherent in the robot. These large deflections produce a much more challenging guidance task than is expected to be encountered in the space environment.

2. Path Description

Within the ASAL an automated path-generation system plans a path from the storage tray to the strut installation location (fig. 4), based on predetermined motion base positions and an ideal kinematic model of the structure. Predetermined motion base positions are used because the current path planner only plans a path for the robot. Although the path planner plans a complete path from the strut storage location to the strut installation location to verify that the robot can reach the installation location, only the portion from strut storage location to the VAP is actually followed. In this region the path is sufficiently far from the structure so that the robot will not collide with deflected struts. The kinematic models of the structure and robot do not include the effects of phenomena, such as gravity deflection, that are of sufficient magnitude to prevent successful strut insertion based on preplanned paths alone.

The VAP was determined experimentally, based on a combination of target pose-estimation accuracy, camera field-of-view requirements, and robot joint limits. At the VAP, the machine vision system processes a video image to determine the target's location and orientation relative to a known frame on the camera (ref. 6). This process is called pose estimation. The pose information is used to guide the robot to the strut installation position.

During assembly, a strut is installed into either one or two receptacles. Installation into two receptacles can be divided into three scenarios, based on the initial receptacle separation in the insertion plane. The insertion plane for a specified strut is defined as the plane containing the centerline of the installed strut and the normals from the centers of the two targets it connects. The three scenarios are (1) receptacle separation distance is equal to the end-effector length, which allows simultaneous capture of both receptacles, (2) receptacle separation distance is greater than the end-effector length, and (3) receptacle separation distance is less than the end-effector length.

Assembly begins with three nodes preattached to the top of the rotary motion base. The first three struts are installed between these fixed nodes (fig. 5) by direct end-effector insertion. Figure 5 depicts the view from the robot after the motion bases have been positioned for strut installation.

The next strut to be installed has the top center node preattached and is installed into a single node. This strut is installed in a cantilevered position, as indicated in figure 6.

The fifth strut is installed in the position indicated in figure 7, which shows an example of the most difficult installation scenario. In this situation the weight of the top center node has deflected the cantilevered strut down

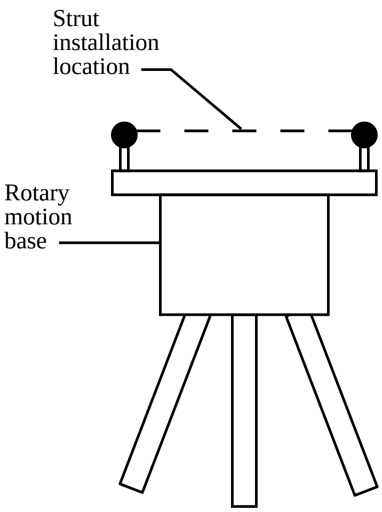


Figure 5. Strut installation allowing direct end-effector insertion.

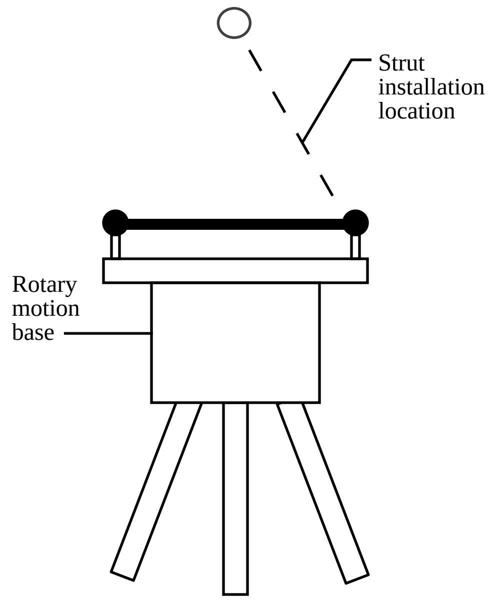


Figure 6. Strut installation using single target.

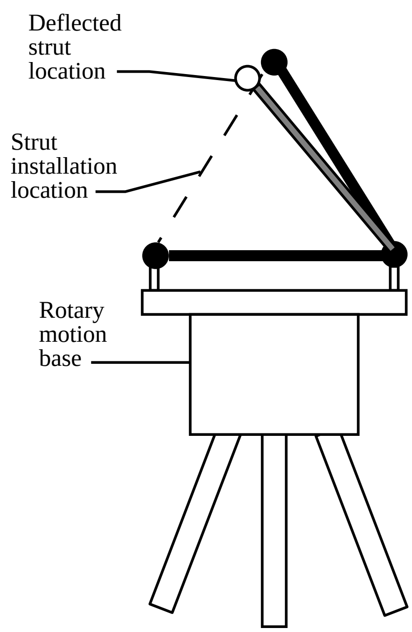


Figure 7. Strut installation requiring movement of cantilevered member outward.

so that the receptacle separation distance is less than end-effector length. The deflected or unattached receptacle must be moved to allow end-effector entry; therefore, the guidance routine must know which receptacle is movable.

After three more struts have been installed, the installation situation shown in figure 8 occurs. In this scenario the cantilevered strut has deflected such that the

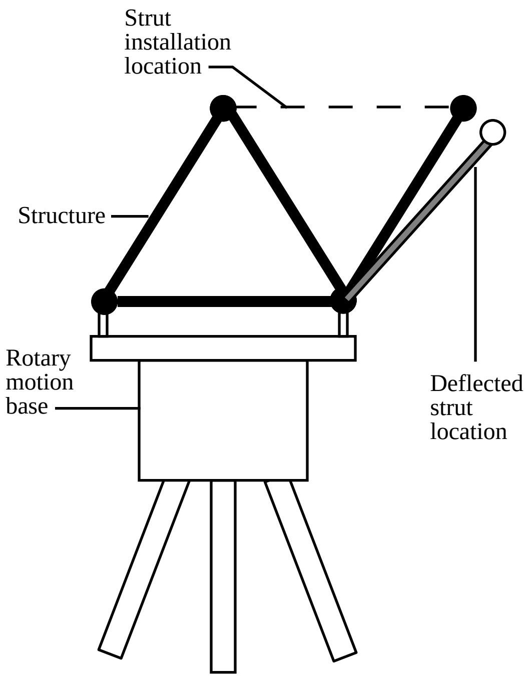
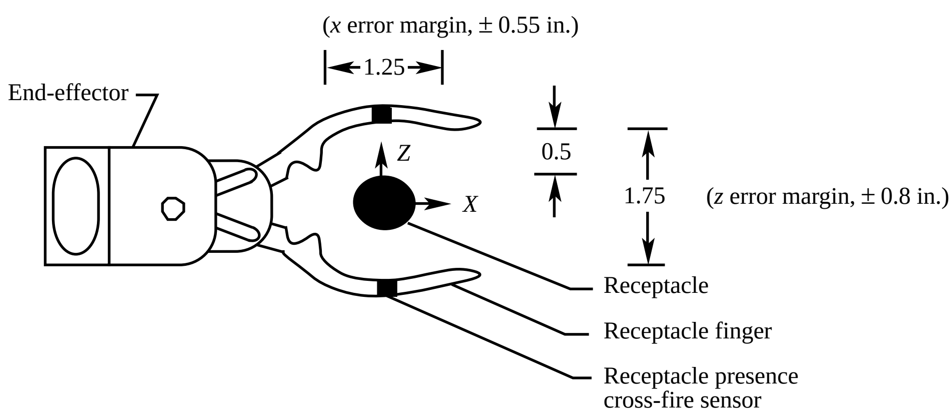


Figure 8. Strut installation requiring movement of cantilevered member inward.

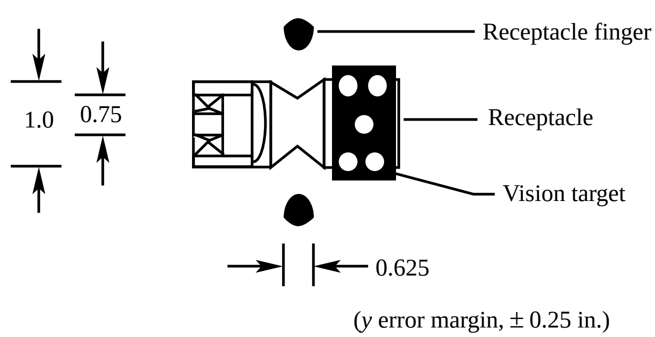
receptacle separation is greater than the end-effector length. The deflected receptacle must be captured and pulled so that the other receptacle can be captured. Again, the guidance routine requires knowledge of which receptacle can be moved.

3. Hardware Details Affecting Receptacle Capture

The position accuracy required from the vision system pose-estimation algorithm is governed by the receptacle capture zone (fig. 9). The receptacle capture zone is determined by a combination of the receptacle vee-groove width and the receptacle finger opening. The tip-to-tip (*Z*-axis) clearance of the receptacle fingers is 1.75 in. Because a receptacle is 0.75 in. in diameter at the base of the vee groove, there is a 0.5-in. error margin in the *Z*-direction before contact is made. The receptacle fingers have been designed with chamfered tips that increase the effective capture zone by ±0.3 in. The fingers tend to slide on the circular cross section of the receptacle when contact is made. Thus, the total error margin along the *Z*-axis is ±0.8 in.



(a) Side view of receptacle and receptacle fingers.



(b) Front view of receptacle and receptacle fingers.

Figure 9. Receptacle capture zone. Dimensions are in inches.

The X-axis capture zone of the receptacle fingers is 1.25 in. long, providing an error margin of ±0.25 in. before contact is made. As mentioned previously, the chamfered fingers and circular cross section of the receptacle increase the effective capture zone by ±0.3 in. for a total capture zone of ±0.55 in. along the X-axis. Along the Y-axis, the receptacle vee-groove provides a total capture zone of 0.5 in., which provides an error margin of ±0.25 in.

Therefore, for successful capture of the strut from the final pose-estimation position, experience with the receptacle hardware shows that the pose estimator must provide information accurate to ±0.8 in. in the Z-direction, ±0.55 in. in the X-direction, and ±0.25 in. in the Y-direction.

A trade-off exists between camera field of view and pose-estimation accuracy. In general, as long as the target is visible, a smaller field of view provides better pose-estimation accuracy because the target (fig. 10) appears larger on the camera image plane. The cameras used in the system, which were selected based on size and electrical requirements, support 6-mm and 12-mm lenses. The 12-mm lens was selected to achieve the required X-axis accuracy of ±0.55 in. Figure 11 shows the camera field of view from the VAP. The tool frame, which is the control reference frame used to specify robot motions, is located between the receptacle fingers at the center of the end-effector Y-axis (fig. 12).

The angular information from the pose-estimation process was unusable. Figures 13 through 15 are plots of the pose-estimator response during a typical series of installations, one plot per axis. Each plot contains two data series. The top series of data corresponds to the range, or X-axis distance data scaled according to the vertical axis on the right, and indicates that this data series encompasses five approaches from the VAP. The bottom data series represents the angular information for the specified axis. The maximum yaw and roll magnitudes were expected to be on the order of 5°, tending toward 0° as the approach progressed. Because of the guidance scheme to be discussed in section 6, the pitch angle was expected to begin at approximately 5° and increase to 15° as the approach progressed. As the plots show, the angular information far exceeds these expected bounds and appears almost random.

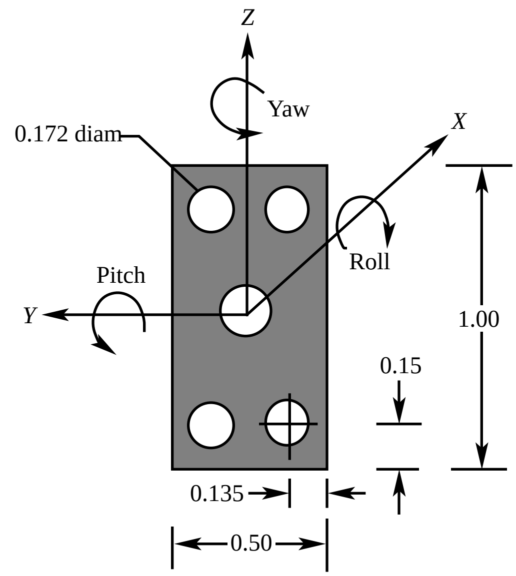


Figure 10. Target geometry. Dimensions are in inches.

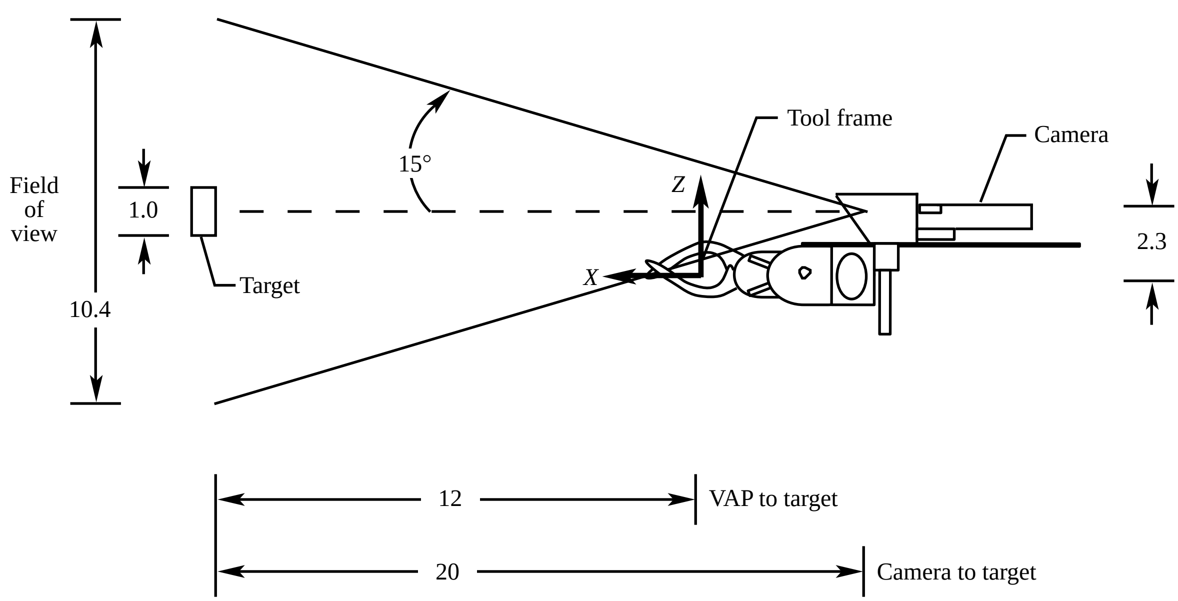


Figure 11. Field of view for 12-mm lens. Dimensions are in inches.

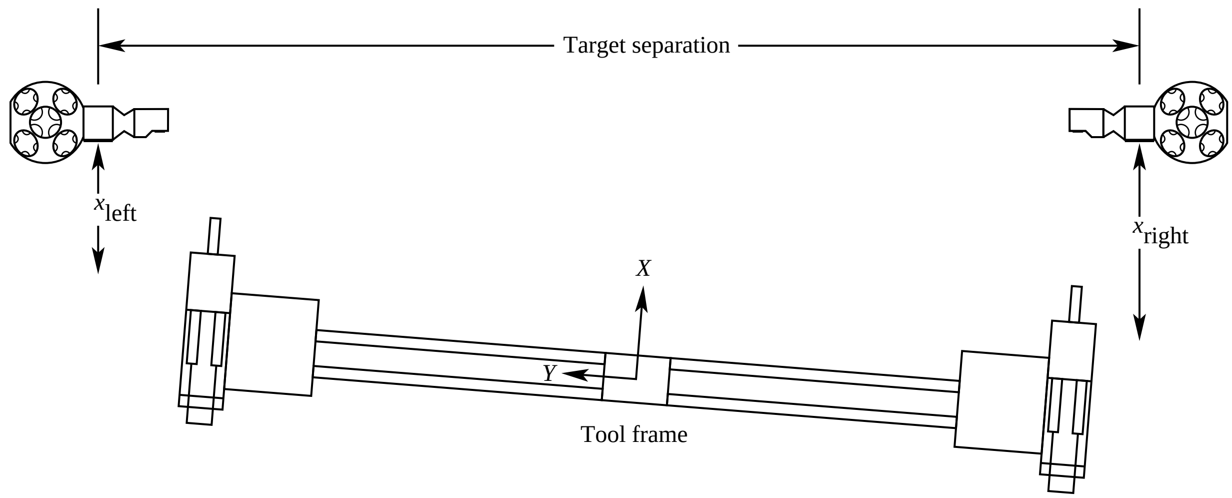


Figure 12. Configuration requiring yaw correction based on *X*-axis or range distances.

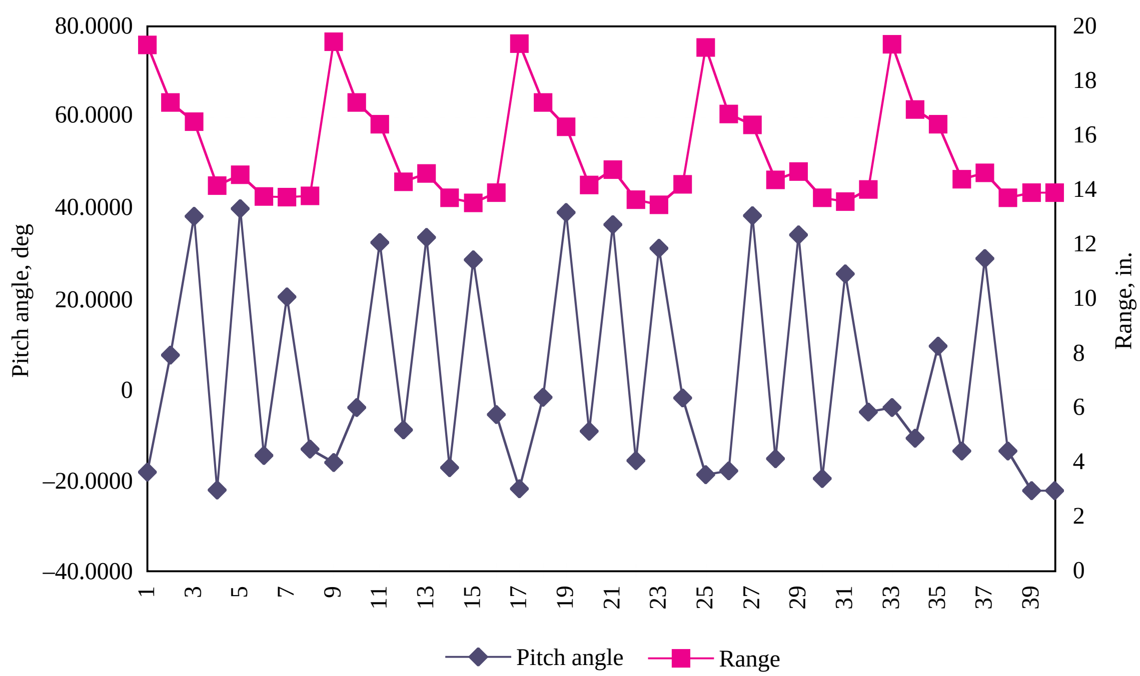


Figure 13. Pitch angle from pose estimator.

The angular errors from a single target may be significantly reduced by shape restoration functions that force the target features to conform to the known geometry. These algorithms are being considered but are not currently in use during assembly operations. Also, alternate target geometries that accentuate the angular errors merit investigation. In contrast to the angular estimation, the translational estimation is very good, consistently falling within ±0.25 in. along all three axes (ref. 6). Thus, the estimation error can be tolerated by the limiting positional error margin of ±0.25 in. along the *Y*-axis.

Comparison of the translational errors to these error margins seems to indicate that the higher accuracy resulting from use of the 12-mm lens is not required. However, a few effects that are difficult to quantify reduce the error margins significantly. First, variations in target fabrication result in slight errors in apparent dot locations.

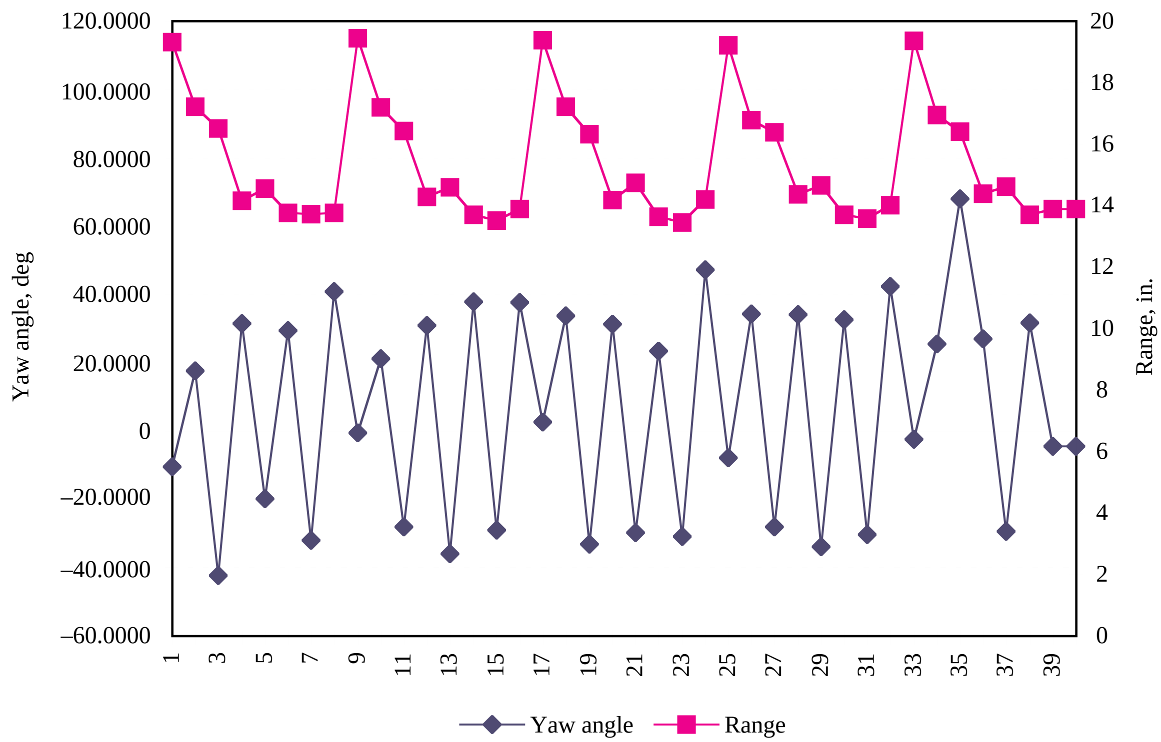


Figure 14. Yaw angle from pose estimator.

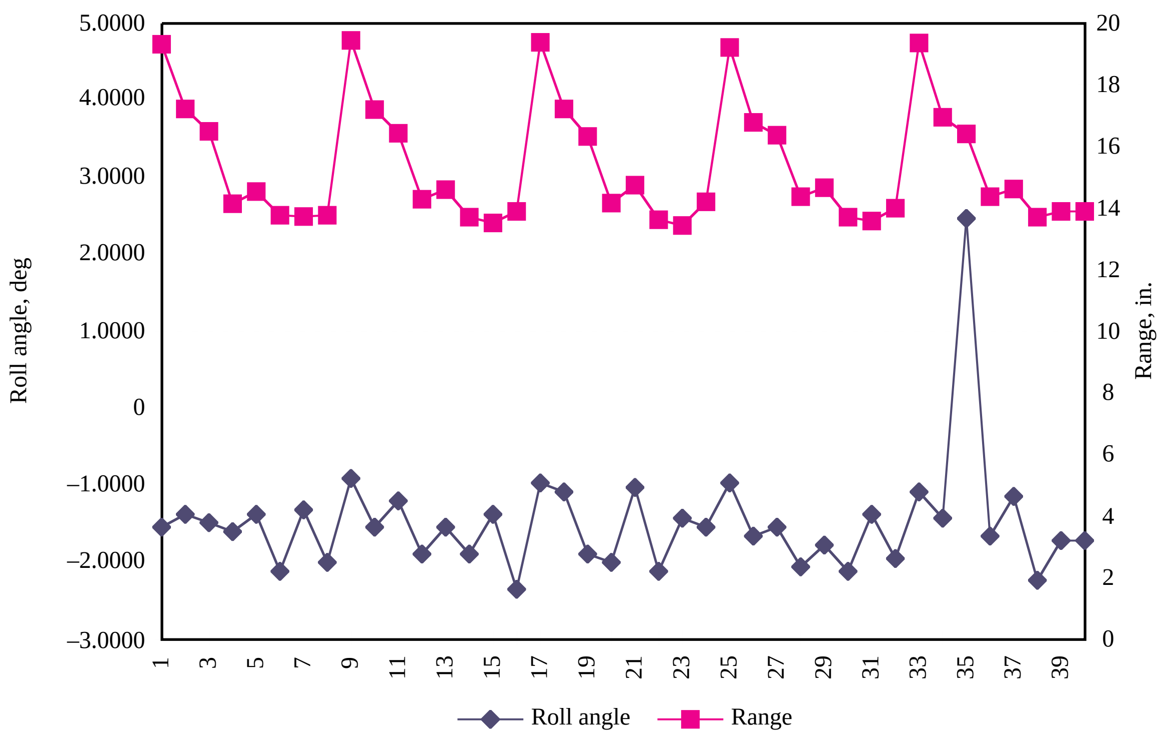


Figure 15. Roll angle from pose estimator.

Second, during operations, the off-axis lighting from the vision system causes shadows, resulting in apparent shifts of the dot centroid locations. These two errors affect the accuracy of the pose-estimation algorithm. The third and most significant factor results from absolute positioning errors of the robot because of end-effector compliance. As will be discussed in section 5, a number of maneuvers are made while pulling a captured strut. These maneuvers exert loads on the end-effector and cause the robot wrist to roll, which must be accommodated by the capture-error margins.

4. Alignment Calculations

When a single target is available, only translation corrections can be made. These corrections are calculated with the information from the camera with the target in view, i.e.,

$$x_{\text{correction}} = x_{\text{left}} \text{ or } x_{\text{right}}$$

$$y_{\text{correction}} = y_{\text{left}} \text{ or } y_{\text{right}}$$

$$z_{\text{correction}} = z_{\text{left}} \text{ or } z_{\text{right}}$$

Usually targets are visible at both ends of the end-effector. Based on the relative location of two targets, the location and orientation of the end-effector can be corrected in five of six axes. Translation corrections in *X*, *Y*, and *Z* are determined by averaging the corrections required to align with each target individually. Thus,

$$x_{\text{correction}} = 0.5(x_{\text{left}} + x_{\text{right}})$$

$$y_{\text{correction}} = 0.5(y_{\text{left}} + y_{\text{right}})$$

$$z_{\text{correction}} = 0.5(z_{\text{left}} + z_{\text{right}})$$

Roll correction is determined by the relative distance of the targets above the receptacle finger centerline, and yaw is corrected by using the difference in range of the two targets from the end-effector. Pitch cannot be corrected because location of the targets does not provide enough information. Two target locations define only a line between the goal receptacles, whereas three target locations are required to fully locate the insertion plane. Successful installation relies on the calculated starting position being within the 2° mating tolerance of the truss joint. Pitch correction was not anticipated to be required because the pitch angle is maintained by the previous connections within the partially assembled structure. In addition, because of the symmetry of the struts and nodes, pitch is not affected by the gravity deflections.

If one considers figure 12, yaw correction may be calculated by

$$\text{Yaw} = \tan^{-1}[(x_{\text{right}} - x_{\text{left}})/\text{target\_separation}]$$

If $x_{\text{left}} < x_{\text{right}}$, the yaw correction required is positive, as shown; otherwise, it is negative. Roll correction can be determined from the relative position of the left and right targets (fig. 16). Roll correction is calculated using a similar formula

$$\text{Roll} = \tan^{-1}[(z_{\text{left}} - z_{\text{right}})/\text{target\_separation}]$$

With the corrections discussed, the robot is guided close to the final strut insertion location, as described in section 5. Note that, when installing a strut into a single target, no angular information is required. The geometric model of the structure is sufficiently accurate to orient the end-effector correctly because the single node is always firmly supported and any gravity deflections are negligible.

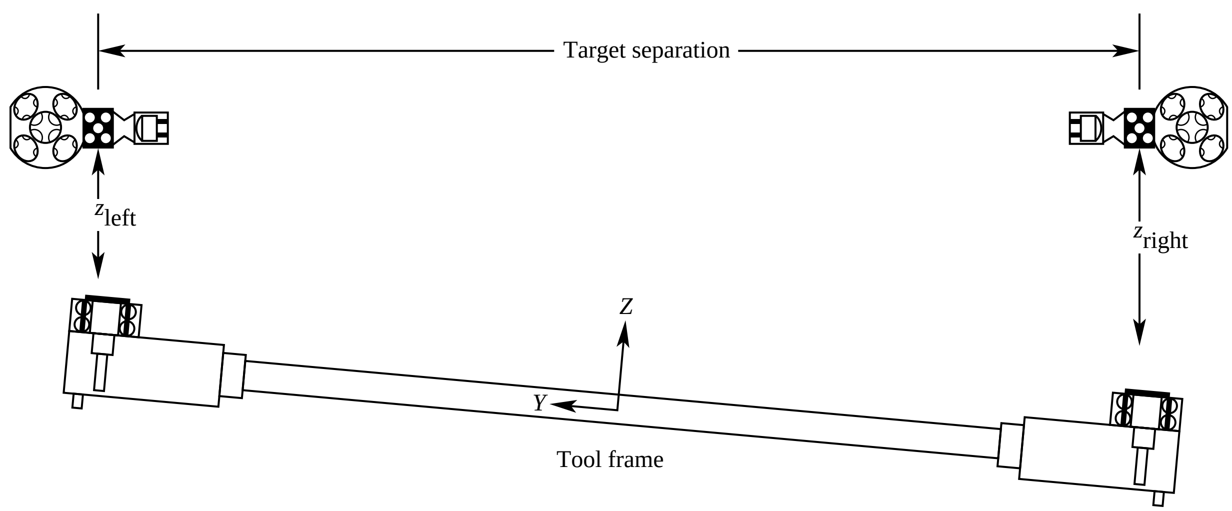


Figure 16. Situation requiring roll correction.

5. Vision Guidance

The guidance task is broken into two stages. The first stage, or approach stage, uses the location of the available targets to align the end-effector close to the final insertion position. During this maneuver, the targets are maintained within the field of view of the vision camera.

To begin the second stage, or grasp stage, the locations of the visible targets are stored. Then the end-effector is maneuvered to capture the structure receptacles in preparation for strut installation. During capture maneuvers, the targets are no longer visible; the maneuver is based solely on the initial stored locations.

5.1. Approach

As detailed in section 4, the Langley vision system provides relative position information necessary to guide the robot to the structure goal frame in preparation for strut insertion. Figure 17 depicts the node and end-effector geometry viewed from behind the robot, looking toward the structure. At the top of the figure, two nodes are shown, each containing a receptacle with an attached target. In a view of the actual structure, additional struts would be attached to the node, but they were omitted from the figure for clarity. At the bottom of the figure, the end-effector and the camera housing outline are shown. To provide a clear view of the target, the robot is directed along a path parallel to the insertion plane, as shown in figure 18. The path is 3.8 in. below the insertion plane to provide a 1.5-in. clearance between the camera housing and potentially preinstalled struts. In figure 17, the most troublesome of the possible preinstalled struts are shown connected at the center of each node, and thus, project out of the page, obstructing direct end-effector entry.

The most common scheme is to direct the robot to a position where the end-effector is either centered relative to two receptacles or aligned with a single receptacle. From the VAP (location A in fig. 18), the vision system directs the robot to move the end-effector toward the structure in a series of steps from location A toward location E. After completion of each step, the camera images of the targets are processed and an appropriate maneuver is formulated. As the end-effector is maneuvered in, the robot is directed to pitch the end-effector to maintain the target within the field of view of the camera. The total pitch accumulated is stored and later removed during the final move from E to the goal frame. The series of steps brings the end-effector tool frame to a distance of 5.75 in. from the final grasp position. This distance was selected to provide sufficient clearance for a *Y*-offset maneuver (section 5.2) used during installation of a strut when the node separation distance does not allow direct end-effector entry. After reaching pose E, the target images

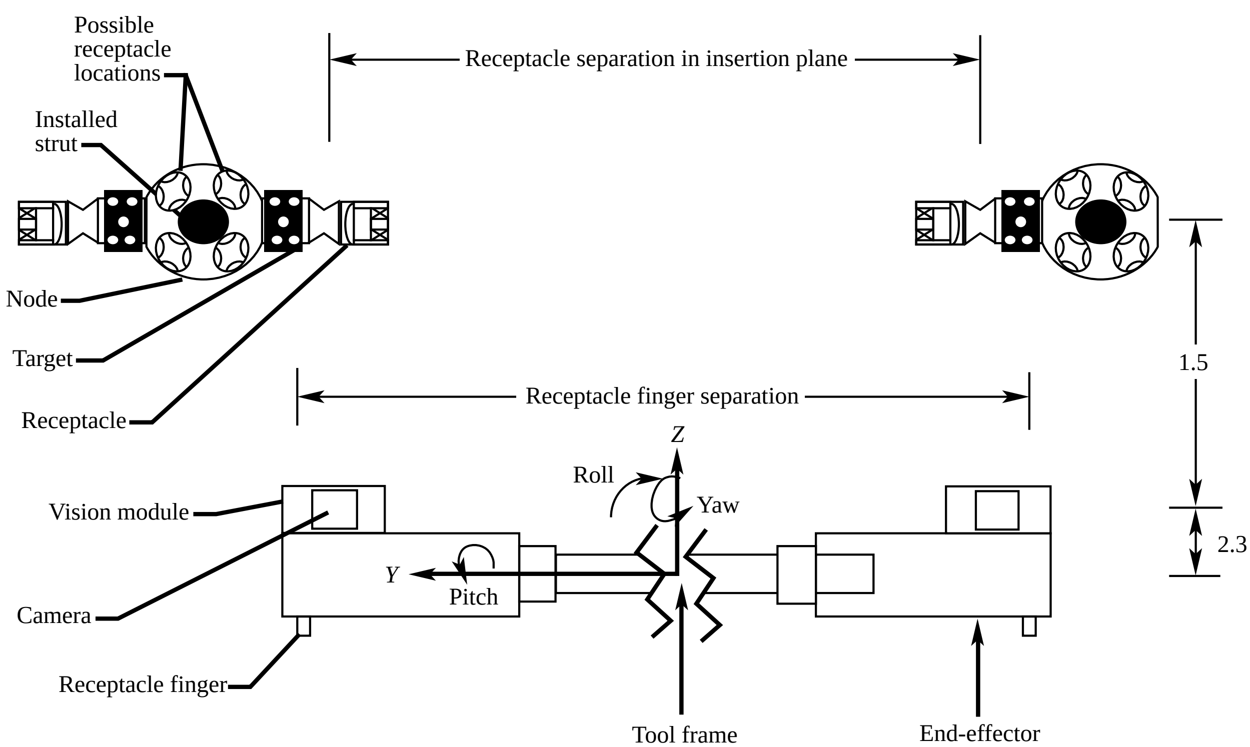


Figure 17. Generic installation geometry viewed from behind robot. Dimensions are in inches.

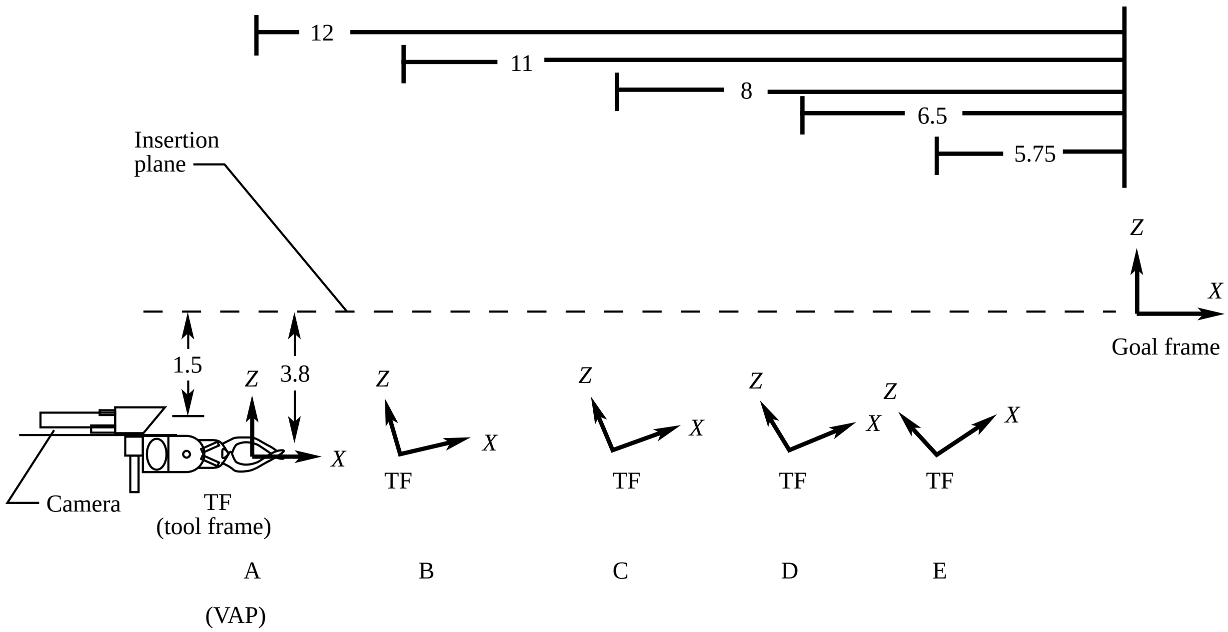


Figure 18. Approach sequence under vision guidance. Dimensions are in inches.

are processed a final time, and the location of each target is stored.

5.2. Grasp Sequence

The objective in the final grasp sequence is to move the end-effector tool frame from position E to the goal frame. During the move, the receptacles of preinstalled nodes are captured in preparation for installation of the strut carried by the end-effector.

When sufficient clearance is available for end-effector entry, the end-effector is moved into the insertion plane by removing the accumulated pitch and translating in the *Z*-direction. Then the end-effector is translated along the *X*-axis to capture the receptacles.

When the node separation is greater than the end-effector length, the guidance routine requires information regarding receptacle and node mobility so that the movable receptacle is captured first. The robot is directed to translate parallel to the *Y*-axis to align the end-effector with the movable receptacle, based on the stored location information. The receptacle fingers open, and the robot is directed to move forward to position the movable receptacle within the capture envelope of the receptacle fingers. Then the fingers close to capture the movable receptacle. Next, force-torque information from a wrist-mounted force-torque system is used to relieve roll loads induced by slight misalignments with the captured receptacle. The robot is then directed to move halfway in the *Y*-direction toward the fixed receptacle, where force-torque information is used again to relieve loads induced by the translation. The loads result from movement of the movable receptacle (fig. 19). In the figure, the movable receptacle on the left has been captured by the end-effector and is pulled toward the fixed receptacle on the right. As the robot moves in a straight line toward the fixed receptacle, the movable receptacle sweeps an arc as it pivots about the attached end. The motion of the movable receptacle along the arc induces a roll about the robot wrist. This roll twists the end-effector out of position so that it is unable to grasp the fixed receptacle. The twist is relieved by directing the robot to roll the wrist, using torque information from the wrist-mounted force-torque sensor. Then the robot is directed to continue along the straight line to position the fixed receptacle within the capture envelope of the remaining open receptacle fingers. The receptacle fingers are closed to complete the capture sequence.

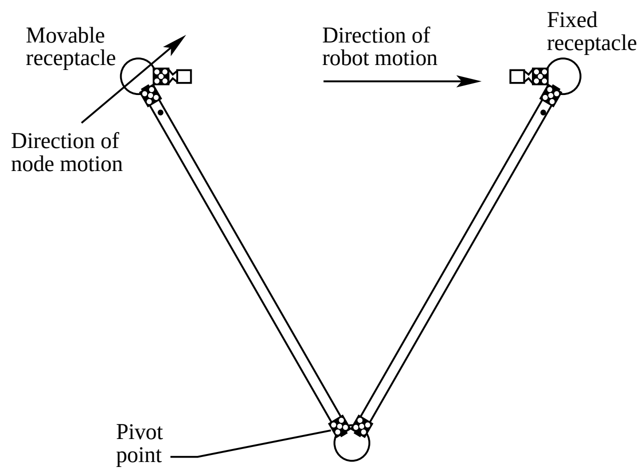


Figure 19. Pivoting induced by straight line motion.

The most difficult scenario occurs when clearance between the two receptacles to be captured is not sufficient for end-effector entry. The movable node must be captured and pushed away from the fixed node until sufficient clearance is available for end-effector entry. Thus, there must be a space adjacent to the fixed node into which the end-effector may protrude while the movable node is being captured. Because the approach to the goal frame is from within the structure, an unobstructed region or access way always exists between previously installed struts. Figure 20 depicts a side view looking from the center of the end-effector toward the left node, which corresponds to position E in figure 18. The end-effector goal frame is shown at the center of the node. The possible existence of the horizontal strut, shown at the top of the figure, constrains the end-effector lateral (*Y*-axis) motions. However, an open triangular region formed by the preinstalled struts (fig. 20) always exists that provides sufficient clearance for lateral motion of the end-effector. The lateral motion is used to capture the movable receptacle and push it into position for strut installation. The capture scenario follows:

1. The robot translates the end-effector in *Y*, which appears to move into the page in figure 20, through the access way to line up with and capture the movable receptacle.
2. The end-effector is moved out of the access way, while pushing the movable receptacle to increase node separation.
3. The end-effector is moved into the strut insertion plane to capture the remaining receptacle.

Figure 21 depicts a two-node capture, where the separation distance is less than the length of the end-effector. The goal strut installation position is designated by a dotted line. In figure 21(a), key components of the facility are shown for reference. Figure 21(b) is a close-up view that shows the insertion plane. The insertion plane, a critical reference feature, is used to explain the end-effector maneuvers.

Figure 22 depicts the seven maneuvers used to capture the receptacles and position the end-effector for strut installation when the receptacle separation distance prevents direct end-effector entry. The bold lines correspond to a line between the receptacle fingers passing through the tool frame. The dashed line is the goal position for strut installation. The insertion plane is shown for reference.

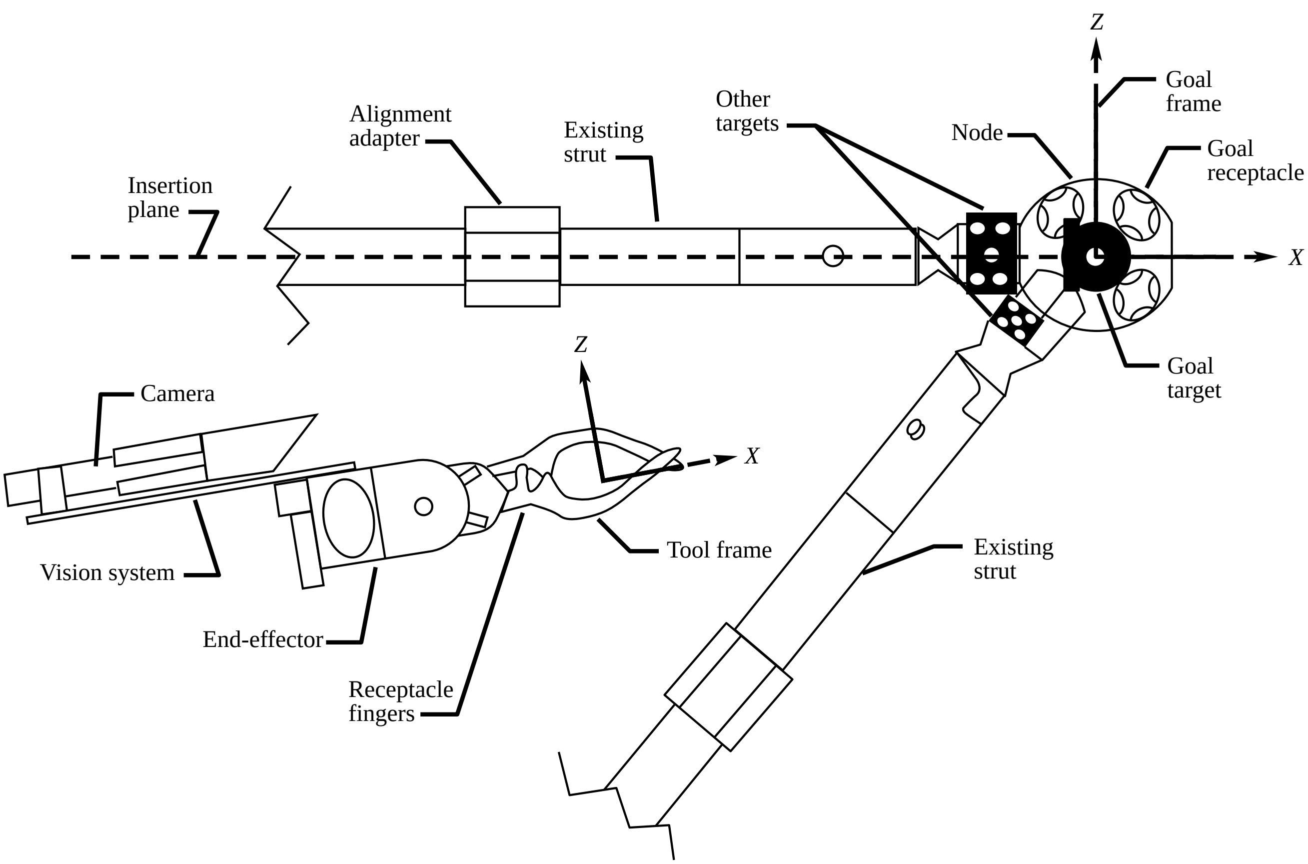
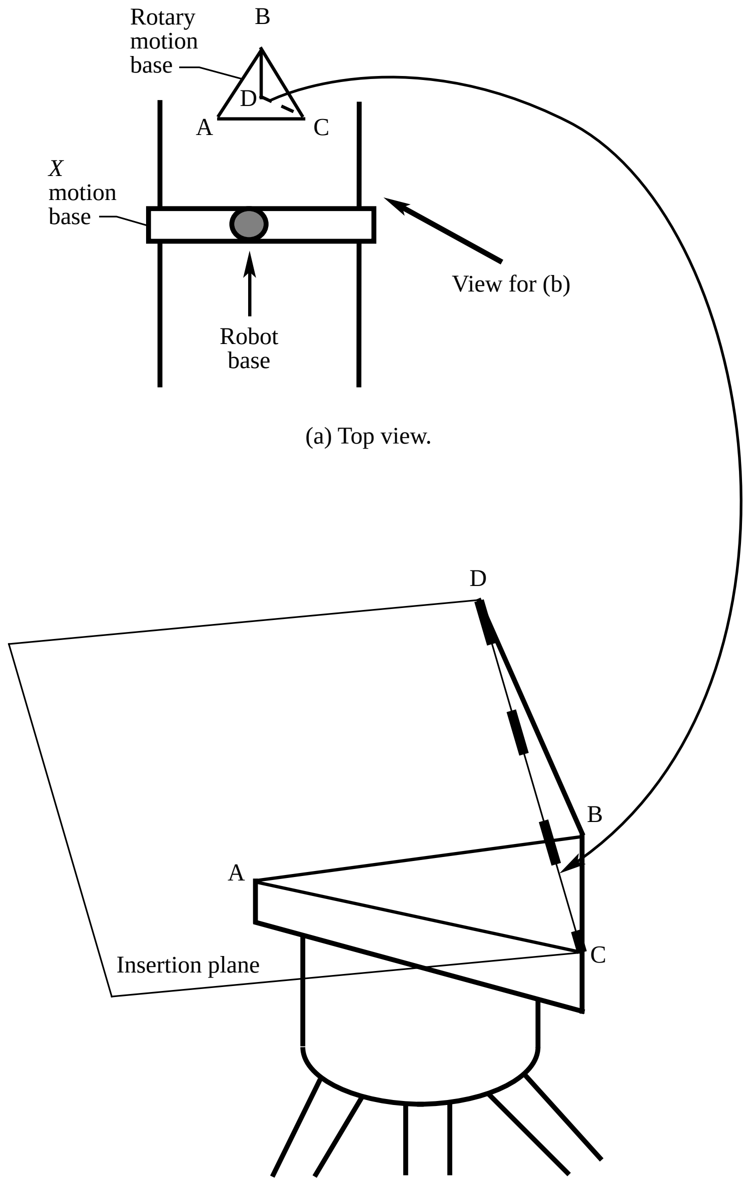


Figure 20. Side view of insertion geometry.



(a) Top view.

(b) Perspective view.

Figure 21. Insertion plane location for example capture maneuver. Strut separation less than end-effector length.

Position 1, shown at the bottom in figure 22, corresponds to the end-effector position E in figure 18. The left receptacle in figure 22 corresponds to the movable receptacle D in figure 21, whereas the right receptacle in figure 22 corresponds to the fixed receptacle C in figure 21. Following the steps shown in figure 22 the capture maneuver proceeds, moving from

1 to 2 Remove accumulated pitch and move end-effector right into access way to enable capture of left receptacle.

2 to 3 Roll about right end (R) to bring left receptacle fingers into the insertion plane.

3 to 4 Open left receptacle fingers and yaw about right end (R) to position left receptacle fingers for capture of left receptacle. Note that the left receptacle fingers remain in the insertion plane during this maneuver. Close left receptacle fingers to capture left receptacle.

4 to 5 Move left receptacle fingers parallel to goal position to pull right side of end-effector out of the access way.

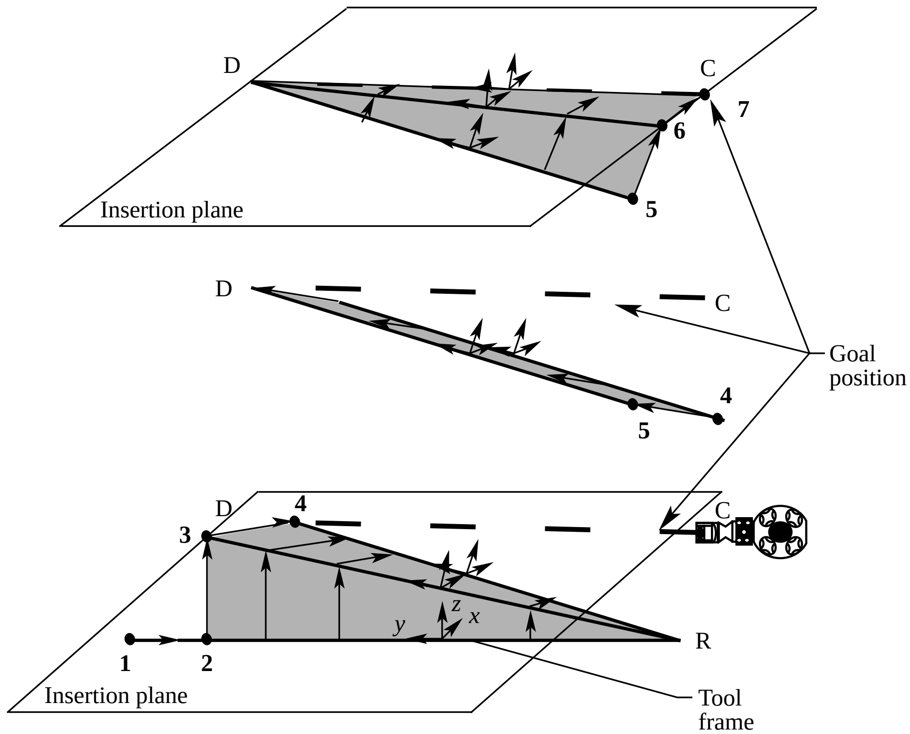


Figure 22. Capture maneuver. Strut separation less than end-effector length.

5 to 6 Open right receptacle fingers and bring them into the insertion plane by rolling about captured left receptacle (D).

6 to 7 Yaw about left receptacle (D) to position right receptacle fingers for capture of right receptacle. Finally, close right receptacle fingers to capture right receptacle and complete the maneuver.

6. System Verification and Manual Override Support

The automated assembly system monitors the success of all strut installation operations. For example, prior to closing the receptacle fingers to capture a node receptacle, the receptacle presence cross-fire sensors shown in figure 9 verify that the receptacle is within the capture envelope. If the receptacle is not within the capture envelope, the system requests manual assistance to reposition the receptacle fingers. If the repositioning also fails to locate the receptacle correctly, the operator may elect to abort the operation. If the operator aborts the operation, the system releases any captured receptacles and moves directly back to the VAP, where the operator is given the opportunity to reinitiate machine-vision guidance or abort the entire installation.

In addition, the operator can suspend system operation at any time. With the system suspended, the operator may request additional status information, abort the current operation, or override faulty sensor readings.

In extreme situations, the operator may be requested to manually direct the robot's motion; for example, when target identification has failed. To date, target identification failure occurred only when the illumination system on the end-effector failed, but the possibility requires that a remote manual backup mode be supported. In the remote manual mode, the operator positions a graphical target overlay over a digitized target image, thus performing the target identification function. This information is then used to guide the end-effector.

7. Operational Experience

During development of the guidance routine, several problems were encountered. First, multiple targets in the proper orientation to satisfy the target identification algorithm may be visible, depending on the geometry. Figure 17 shows an example where two receptacles are visible on opposite sides of the target node. Depending on which end-effector camera is being used, the target closest to the end-effector midpoint is selected. This information is stored in the assembly system database. In this situation, if only one target is located in the field of view of the camera, there is no way to determine if the correct target has been located. Thus, when two targets should be visible, as indicated by the executive database, and only one target is located, the system requests operator confirmation. Further marking on the targets could eliminate this problem and relieve the need for the database information.

A second problem involves the intensity of the artificial lighting. One light level was assumed to be sufficient for locating the targets throughout the 12- to 5.75-in. range. This assumption, however, was not valid. Lights sufficiently bright to illuminate the target at 12 in. saturate the camera CCD pixel elements and cause the target dots to blur and bleed together at 5.75 in. Use of variable intensity lighting solves the problem. Thus, as the end-effector moves closer to the insertion position, the light intensity is reduced.

A third problem involves initial target identification. In some instances, one of two expected targets is not located because it is either not within the field of view of the camera or not sufficiently illuminated. To locate the second target, a search is implemented about the first target found. After positioning the appropriate end of the end-effector over the located target, a roll search begins in 1° increments up to ±3°. If the target still is not located, the end-effector is yawed 1° to expand the field of view outward, and the roll search is repeated. The entire cycle is repeated until the robot has yawed 3°. To date, the search algorithm has located all targets not originally visible from the VAP.

The fourth problem involves the target construction. The targets were initially formed by laminating an aluminum backing, reflective tape, and flat black mask. However, because of incidental contact, an occasional target mask would be misaligned. To correct this problem, the target mask is extended and rolled back over the aluminum backing (fig. 23). This change eliminates the problem of shifting masks.

Placement of the vision system above the end-effector centerline was necessary in this application. However, this placement significantly complicated development of the guidance algorithms and should be avoided in future applications. Likewise, video from the vision system would have been considerably more useful if it gave a clear view of the final approach.

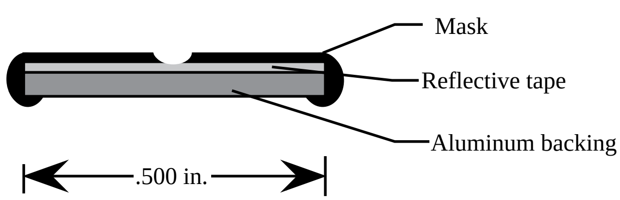


Figure 23. Cross section of target through center.

Ideally, the camera should be centered on the target at all times, but as a minimum, the target should be visible during the receptacle capture operation. Maintaining target visibility produces several desirable results. First, the field of view needed to track the target is minimized, thereby increasing the pose-estimation accuracy. Second, maintaining target visibility allows continuous adjustment until the receptacle is captured, which simplifies the control design. Third, and most important, the ability to continuously adjust counteracts errors caused by end-effector compliance as a captured strut is being pulled into position.

8. Preliminary Results

During tests, the system successfully guided receptacle capture in all cases. In fact, because of the success of the system, all taught paths have been discarded in favor of calculated paths as a first step toward an automated path-planner interface. The calculated paths include the VAP as a subgoal that positions the cameras 1.5 in. from the expected strut insertion plane and 12 in. from the final insertion position. This location corresponds to pose A in figure 18 and provides a field-of-view area of approximately 10 in. about the expected receptacle location. This initial location has been sufficient to allow acquisition of at least one target and to counteract all deflections and misalignments caused by gravity and robot inaccuracies. When two targets should be visible but only one is located, the search algorithm always successfully located the second target.

9. Areas for Future Work

Work to improve the angular information from the targets is needed. The most promising techniques use nonplanar targets to accentuate the angular errors. Also, additional work is required on target patterns that allow the system to determine whether the proper target has been located when two targets are within the field of view of a single camera.

The search algorithm used to locate targets initially may be expanded to include a pitch search for added robustness. However, the robot cannot perform pitch adjustments in all cases because of robot wrist-pitch limitations. The possibility of a pitch limitation implies that the search would require knowledge of the robot configuration or, preferably, a more robust planning algorithm that guarantees sufficient pitch range at the VAP.

The overall speed of the vision-path segment could be improved by using a tracking approach rather than the current incremental step approach. The tracking approach is a straightforward enhancement because all image processing can be performed on captured images as the robot moves the end-effector.

The guidance algorithms may also be applied to other assembly operations, such as the acquisition of struts from the trays.

10. Concluding Remarks

Use of a vision system to provide final guidance for receptacle capture has significantly improved the reliability and robustness of the Automated Structural Assembly system. The vision system represents a significant step in the development of a flight-ready system because it allows robot motions to be planned and verified by an automated path planner. Modeling inaccuracies are automatically compensated for at run time by the vision guidance system, which allows arbitrary structures to be confidently built without large-scale verification models. Hardware test facilities will be required only for a limited subset of the structure to verify models, hardware connection techniques, and system software.

NASA Langley Research Center
Hampton, VA 23681-0001
June 20, 1996

11. References

1. Rhodes, Marvin D.; Will, Ralph W.; and Wise, Marion A.: A Telerobotic System for Automated Assembly of Large Space Structures. *The 21st Century in Space, Volume 70—Advances in the Astronautical Sciences*, George V. Butler, ed., American Astronaut. Soc., 1988, pp. 111–129. (Available as AAS 88-170.)

2. Lee, Gordon K. F.; Anderson, Dave; Rockoff, Lisa; Garvey, John; and Filatovs, Juri: On-Orbit Assembly of Large Space Structures—A Mars Aerobrake Mock-Up Study. *Proceedings of the Third International Conference of Engineering, Construction, and Operations in Space—III: Space ‘92*, Vol. 1, ASCE, May–June 1992, pp. 999–1009.

3. Chua, Koon M.; Johnson, Stewart W.; and Sahu, R.: Design of a Support and Foundation for a Large Lunar Optical Telescope. *Proceedings of the Third International Conference of Engineering, Construction, and Operations in Space—III: Space ‘92*, Vol. 2, ASCE, May–June 1992, pp. 1952–1963.

4. Coppa, A. P.: Robotic Assembly of Truss Beams for Large Space Structures. *J. Spacecr. & Rockets*, vol. 32, no. 4, July 1995, pp. 680–685.

5. Sydow, P. Daniel; and Cooper, Eric G.: *Development of a Machine Vision System for Automated Structural Assembly.* NASA TM-4366, 1992.

6. Herstrom, Catherine L.; Grantham, Carolyn; Allen, Cheryl L.; Doggett, William R.; and Will, Ralph W.: *Software Design for Automated Assembly of Truss Structures*. NASA TP-3198, 1992.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
November 1996

3. REPORT TYPE AND DATES COVERED
Technical Paper

4. TITLE AND SUBTITLE
A Guidance Scheme for Automated Tetrahedral Truss Structure Assembly Based on Machine Vision

5. FUNDING NUMBERS
WU 233-03-03-02

6. AUTHOR(S)
William R. Doggett

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-0001

8. PERFORMING ORGANIZATION REPORT NUMBER
L-17538

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TP-3601

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified–Unlimited
Subject Category 61
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The Automated Structures Assembly Laboratory (ASAL) is a unique facility at Langley Research Center used to investigate robotic assembly of truss structures. An industrial robot equipped with a special purpose end-effector has been used to assemble 102 struts into an 8-m-diameter structure, as well as beam structures. Initially, robot motions required to construct the structure were developed with iterative manual procedures. However, this approach is not suitable for in-space applications because of astronaut and time and safety considerations. Thus, an off-line geometric path planner combined with a compact machine vision system has been developed. By providing position information relative to passive targets on the structure, the vision system guides the robot through a critical region, beginning approximately 12 in. from the structure and proceeding to a position where the structure is grasped prior to strut insertion. This approach offsets model uncertainties in the path planner and greatly increases operational reliability. This paper presents details of the machine-vision-based guidance algorithms used during structure assembly.

14. SUBJECT TERMS
Automated construction; Guidance; Machine vision

15. NUMBER OF PAGES
18

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	